Economia Aziendale Online

Business and Management Sciences
International Quarterly Review

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Pavia, December 31, 2023
Volume 14 - N. 4/2023

DOI: 10.13132/2038-5498/14.4.1279-1303

www.ea2000.it
www.economiaaziendale.it

Pavia University Press

Electronic ISSN 2038-5498
Reg. Trib. Pavia n. 685/2007 R.S.P.

Economia Aziendale Online – Business and Management Sciences International Quarterly Review
SPECIAL ISSUE - Vol. 14-4/2023 - DOI: 10.13132/2038-5498/14.4.1279-1303

Description of a dynamic simulation model for the control of the complex ecosystem of an infrastructural project

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Cite as:

Iovino, G. (2023). Description of a dynamic simulation model for the control of the complex ecosystem of an infrastructural project. *Economia Aziendale Online, 14*(4), 1279-1303.

Section: *Refereed Paper*

SPECIAL ISSUE 2023

Received: October, 2023
Published: 31/12/2023

ABSTRACT

This article describes the dynamic simulation model of the construction works of a large industrial infrastructure (Power Plant). The construction activity is a dynamic activity as the complete realization of the infrastructure is achieved through intermediate states of assembly of partial structures, which evolve over time until reaching the final planned configuration. The on-site workforce that performs the construction represents the system, that is, by definition, a set of agents that operate in a coordinated manner according to a predefined project and program. The objective of the system is to complete the work within the given total time while remaining within the planned cost. The result of the construction activity is considered as the emerging structure of the resource system used for that purpose. The construction activity is analyzed with a systemic approach to highlight the causal relationships between the main variables involved in and, consequently, identify the key parameters of the process. Among the key parameters are included: the time constants of mobilization and demobilization of workforce, their physical productivity of assembling the various substructures, the structural growth factor that characterizes the topology of the elementary substructures. The proposed model is based on the qualitative causal loop analysis, necessarily simplified to highlight the underlying principle, followed by a Stock & Flow quantitative methodology. It starts from a real project whose data relating to the employed resources and their performance in the field (patterns) were analyzed a posteriori. The model allows Project Managers to perform "what-if" analysis for initial and intermediate states of progress of the works, taking into account the main parameters affecting the process in order to achieve the objective in a controlled manner. The methodology is completely general and therefore can be applied to any type of structure.

Questo articolo descrive il modello di simulazione dinamica dei lavori di costruzione di una grande infrastruttura industriale (Power Plant). L'attività di costruzione è un'attività dinamica in quanto la completa realizzazione dell'infrastruttura si attua attraverso stati intermedi di montaggio di strutture parziali, che evolvono nel tempo fino a raggiungere la configurazione finale prevista. La manodopera in cantiere che esegue la costruzione rappresenta il sistema, cioè per definizione, un insieme di agenti che operano in maniera coordinata secondo un progetto e un programma predefiniti. L'obiettivo del sistema è quello di completare il lavoro entro il tempo totale stabilito rimanendo entro il costo pianificato. Il risultato dell'attività di costruzione è considerato come la struttura emergente del sistema di risorse utilizzato a tale scopo. L'attività di costruzione viene analizzata con un approccio sistemico per evidenziare le relazioni causali tra le principali variabili coinvolte e, di conseguenza, identificare i parametri chiave del processo. Tra i parametri chiave sono inclusi: le costanti di tempo di mobilitazione e smobilitazione della forza lavoro, la loro produttività fisica di assemblaggio delle varie sottostrutture, il fattore di crescita strutturale che caratterizza la topologia delle sottostrutture elementari. Il modello proposto si basa sull'analisi qualitativa del ciclo causale, necessariamente semplificata per evidenziare il principio di base, seguita da una metodologia quantitativa Stock & Flow. Si parte da un progetto reale di cui sono stati analizzati a posteriori i dati relativi alle risorse impiegate e alle loro performance sul campo (pattern). Il modello consente ai Project Manager di effettuare analisi "what-if" per gli stati iniziali e intermedi di avanzamento dei lavori, tenendo conto dei principali parametri che influenzano il processo al fine di raggiungere l'obiettivo in modo controllato. La metodologia è del tutto generale e quindi può essere applicata a qualsiasi tipo di struttura.

Keywords: Simulation, Management, Construction, System Dynamics, Control, Causal loop Diagrams, Stock and Flow

1 – Introduction and Background

The construction activity is by its nature a dynamic process as the complete construction of an infrastructure is achieved through intermediate states of assembly of partial structures that evolve over time until the final planned configuration is obtained.

The creation of a large infrastructure requires the coordinated action of a significant amount of people with different specializations who have to operate within a well-defined period. The relationship between the financial resources allocated to the project - which are associated with quantities of materials, means of construction and workforce - and the time for carrying out the work, reflects the dynamic nature of the projects.

The on-site resources, which carry out the construction, represent the system that is the object of this study, as they constitute a set of agents that operate in a coordinated and controlled manner according to a predefined project and program. The objective of the system is to complete the work in the target time remaining within the planned cost.

Given the tendency of the clients of the infrastructural projects to reduce the duration of the projects as much as possible, the construction companies have to increase the overlap of the project parts as much as possible. This contributes to increase the complexity of the system because the resources that work on one portion of the works may be affected in their performances by those resources working in other close areas.

Such a complexity of the construction due to the simultaneous execution of its parts is often increased by the design phase, which being by its nature iterative, triggers loops of rework that cause Disruption and Delay and eventually affects the construction productivity (Eden *et al.*, 2000; Howick *et al.*, 2017; Howick & Eden, 2001)

McKinsey & Company (2020) states that construction represents the largest industry globally, worth 13% of world GDP but it does not stand out for its performance. Delay and extra cost are unfortunately the norm.

PricewaterhouseCoopers (2013) reports a statistic carried out by the Construction Industry Institute (USA) on 975 industrial projects of various sizes, found that only 5.4 percent of these were able to respect the budgeted programs and costs. Among the main causes, if not the main cause, of these disappointing results is attributed to a poor forecast estimate of times and costs.

As regards in particular large projects (Megaproject), Flyvbjerg (2014) reports that the statistics confirm what is called the "iron law of Megaproject" that is, nine out of ten end late with extra costs that frequently reach up to +50 percent and in some cases even higher. Especially in large projects, there is what has been defined as "strategic misrepresentation" or a voluntary underestimation of the risks associated with the project with the aim of encouraging investment.

Fortunately, according to PMI's Pulse of Profession (2017), project planning and management techniques have been refining more and more during last 30 years and this improvement has reduced the negative impact on performance. However, the project results remain poor and, according to Girmsheid & Brokmann (2007), they seem difficult to improve due to the intrinsic complexity of the projects.

Such a high percentage of delays and extra costs would suggest a sort of systematic error in planning and control since, statistically, the deviations that occur during construction should act both negatively and positively. Therefore, we wondered whether it is possible to improve the construction process modeling in order to highlight the underlying logic and the key parameters of that process.

The article deals with the idea to reconsider the construction process taking advantage of Causal Loop Diagrams (CLD) and Stock and Flow (S&F) methods. It is useful to highlight that:

– Meadows (2008) and Stermann (2000) provides the basis for the S&F simulation method and a large collection of examples in different fields of application.

– Lyneis & Ford (2007) paid a particular attention to the use of CLD and S&F method for the solution of construction management problems.

– Iovino (2022) specifically addresses the application of the S&F method to the project described in this article, which was the base for the setup of the overall project model.

This analysis was possible thanks to the availability of ex-post data concerning the amount of the workforce employed (patterns) for the construction of an actually built plant referred to below as the "reference plant". These data were disaggregated by type of work, i.e. civil, mechanical works, etc., and by purpose of the pattern, i.e. initial planning (target data) and final balance (actual data).

Below we highlight the results of the qualitative analysis of the process summarized in the Causal Loop Diagrams (CLD) of the various processes and the translation of these logics into modeling for the quantitative simulation of the process typical of system dynamics (SD) based on the Stock and Flow (S&F) method.

2 – Methodology

The data collected for the reference plant concerns the forecast hours of work to be spent on site during construction (patterns) as well as those actually spent. The forecast ones are analyzed to identify the logic underlying the construction process using the qualitative CLD technique. The identified logic of the construction process allows highlighting its characteristic parameters. Subsequently, the CLDs resulting from the analysis are translated into a quantitative S&F

modeling in order to be able to reproduce the forecast trends and extrapolate the simulations to those situations that differ from the reference one.

See the APPENDIX for the definitions of used variables, the meaning of the terminology and the explanation of mathematical relationships used below.

2.1 – *Splitting the overall pattern into its four main forecast patterns*

The patterns analyzed below concern the use of resources for the construction phase of the reference plant. We take it for granted, due to the direct involvement of the author, that the work done prior to the construction, i.e. the design and procurement of materials, did not affect significantly those patterns during the construction it means a minor impact of rework or change orders.

Figure 1 shows the monthly hours planned to be spent and actually spent in the construction of the reference system (left-hand scale: planned values in blue, actual values in red) and the relevant cumulative man-hour values (right-hand scale x 1000: target values in blue, actual values in red).

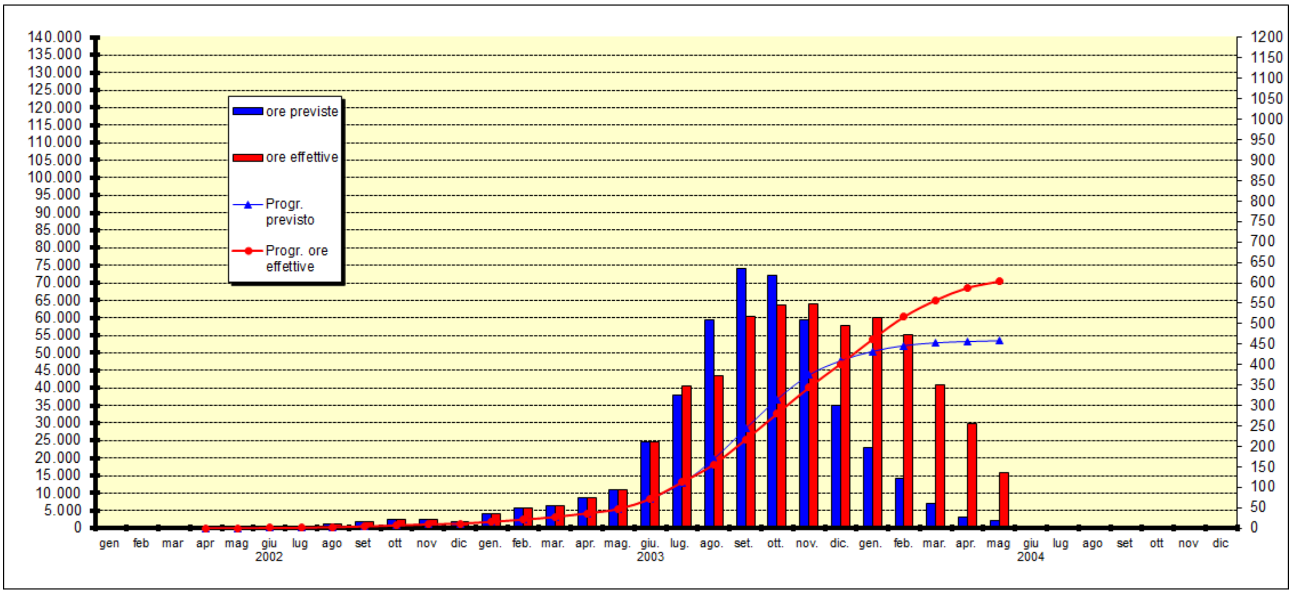

Fig. 1 – Spent Man-hours at site: Planned (Blue) and Actual (Red)

As can be seen from Figure 1, the actual hours were higher than those budgeted, specifically around 600,000 actual hours compared to 450,000 budgeted (+33%) with a "shift" to the right of their distribution (the blue peak is located between Sept-Oct 2003, the red one between Nov-Dec 2003). The histogram in the figure is the sum of several histograms of individual processes whose main ones are the following four: civil works, structural assembly, piping, electro-instrumental works.

The Figure 2 disaggregates the curves of the four processes mentioned above into the planned (or target) works which lead to a total of 319,000 man hours (1596 man months) out of an overall total estimated for the entire project of approximately 450,000 man hours (2250 man months). The data diagrams of hours (planned to be worked as well as actually worked) are transformed into FTE (Full Time Equivalent) head count by dividing the total monthly hours by the value of 200 man-hours/month recorded during construction.

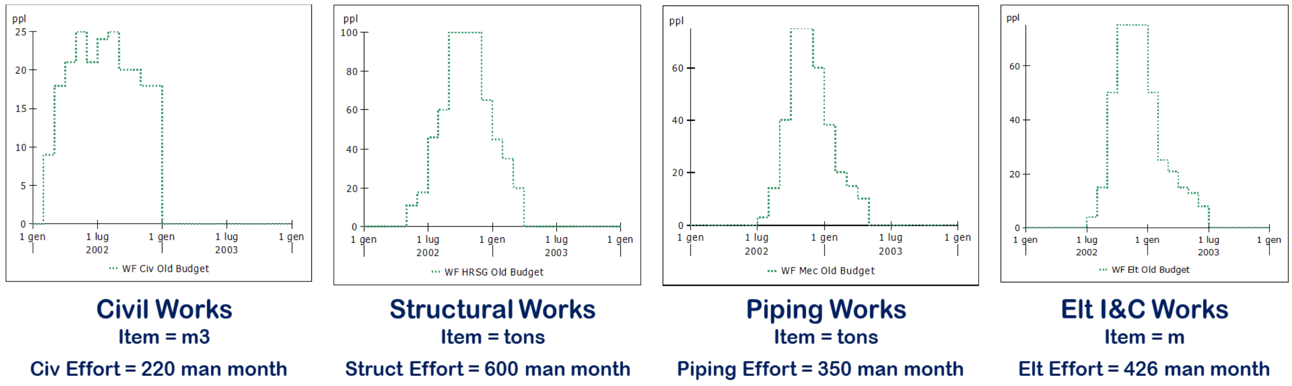

Fig. 2– Planned Workforce Histograms (Patterns) of the four WP – Data

We will see later how to deal with the four final actual curves of the red histogram. For the moment, let us analyze the target curves.

2.2 – *Detailed description of the workforce planned patterns*

The qualitative analysis of the four histograms in Figure 2 shows the following common characteristics:

1. They all are "bell" shaped (which correspond to "S" shapes of the relevant progress curves) that start from zero, reach a maximum value and return to zero.
2. They all have an asymmetrical shape between the phase of increasing resources (mobilization) and that of decreasing resources (demobilization).
3. They all have a trend with peaks that reach approximately 2.4 times the average value, especially in the case of piping assembly.
4. All patterns have the demobilization phase with a negative derivative (outgoing flow) increasing (tending to zero) similar to an exponential trend.

The pattern of civil works differs from the other three due to the shape of the mobilization phase. Furthermore, this WP has a very fast demobilization phase, shorter than the one-month time resolution. We will see later how this trend can be explained for the purposes of the model.

The four curves present the planned quantitative data shown in Table 1.

Table 1 – Planned data of the 4 WPs

Work Package	Duration (months)	Effort (man months)	Average Workforce (units)	Item	Productivity (item/ppl/month)
Civil	11	220	20	m^3	46,2
Structural	11	600	55	ton	1,67
Piping	10	350	35	kg	860
Elt I&C	12	426	36	m	70,6

The individual WPs have the following characteristics.

A – *Civil works.* The civil works essentially consist of the construction of a large reinforced concrete foundation (Figure 3).

Fig. 3– Civil Works - foudation

The civil pattern indicates a rapid mobilization phase of approximately 3 months with initial derivative >>0, then decreasing over time, an almost asymptotic intermediate phase of approximately 8 months and a very rapid demobilization phase of less than a month. This is a rather different trend from that of the other patterns which is interpreted, as will be seen better below, with the characteristic of a continuous massive structure which is typical of the concrete foundation.

B – *Structural assembly.* The bulk of the structural work consists of the assembly of a large steam-generating component for the generation of electricity in the steam turbo generator. The data indicates an average presence of 55 people that reaches a peak of around 100 units in the central months. The pattern of assembly resources has a more symmetrical shape compared to civil works, in particular it has a "peak" factor (maximum resources on average resources) equal to almost 2. Mobilization lasts approximately 3 months, therefore slower than the civil one with increasing derivative (i.e. incoming flow). The central stationary phase is quite long (about 4 months) and demobilization lasts about 3 months. The structure to be assembled is impressive (approximately 30 meters high by 20 meters wide and the same depth (Figure 4) and has the characteristic of a strong modularity as it consists in the assembly of sectors of load-bearing structure within which heat exchange modules are assembled. The construction includes also relatively small tanks and connecting pipes.

Fig. 4 – Structural works – Steam generator Casing

We will see later that the modularity of the structure is important for giving an interpretation of the assembly pattern.

C – ***Piping assembly.*** The subject structure is a piping network for the distribution of water and steam. The resource data indicates a peak of approximately 80 units therefore with a peak factor of 80/35 = 2.28. The peak factor of these jobs is even greater than the structural work. The asymmetry between the mobilization phase, which is rapidly increasing, and the demobilization phase, which has a typically exponential decreasing shape, is very evident. The central steady phase lasts only 2 months out of the total 10. Like all distribution networks, the structure is branched with a root element, which includes the pumping system and related collector and a series of distribution branches.

D – ***Electrical and I&C assembly.*** These works concern the installation of cable networks for the distribution of electricity and signals within the plant. The data indicates a peak of approximately 80 units, therefore with a peak factor of 80/36 = 2.22. The peak factor of these jobs is always high. The asymmetry between the mobilization phase, which is rapidly increasing, and the demobilization phase, which has a typically exponential decreasing trend, is evident. The central steady phase lasts approximately 3 months out of the total 12.

Like all distribution networks, the structure is branched like that of the piping but, as we will see later, its assembly is less constrained due to the greater ease of routing the cables compared to the pipes. Furthermore, the cable network starts and arrives at intermediate structures (electrical panels), which makes installation more flexible. Ultimately, it could be considered that this process represents an intermediate state between civil works (which are free of constraints) and the pipe network (which is a branched structure).

2.3 – *Patterns Interpretation – Causal Loop Diagrams (CLD)*

Before proceeding with the interpretation of the patterns, it is the case to refer to Appendix 1 for the meaning of some parameters and variables used below as well as the relationships between them.

2.3.1 – Description of the planned workforce mobilization pattern for not constrained structures using CLD

Let us imagine starting planning the WP of the civil work with the support of the Site Manager. We start from the basic data, i.e. from the quantity of material to be assembled, for example let us assume a scope of N_T items (m^3). Then we estimate, through the typical standard hours of the civil works, the average productivity required by the workforce that we assume to be P (m^3/ppl/month). It means that the work effort or the man months necessary for the works will be N_T/P.

Finally, if we want to finish the works within T months, then we can assess the average number of resources W that can work in parallel being $W= N_T/P/T$.

W people is the average number of resources to be distributed along time T on the WP bar of the Gantt program during which N_T/T items will be mounted per unit of time.

In reality, it is not possible to mobilize instantly all the W resources from the beginning of the work program. This may happen, for example, due to the temporary unavailability of work force specialized in that specific process, or because the process itself requires interruptions due, for example, in the case of civil works, to the need for the concrete to mature or even due to the required time for training.

Under those rather frequent hypotheses, we will have a non-uniform distribution of resources on the time bar of our Gantt program. Resources, which start from zero, will have to grow until they reach a value slightly higher than the average value previously calculated, due to the need to recover the initial delay. Finally, close to the end of the works, resources will be reduced to zero. However, for the moment, let us ignore the demobilization phase, which will be discussed later on. We can translate the above logic, limited to the mobilization phase, into the following CLD in Figure 5.

To explain the CLD, we start from the dashed box in which the work to do, the time available, the required erection rate and the required workforce appear. The Time available for completion is continually decreasing due to the increase of current time. The reduction of the time available (for the same given scope) causes an increase of the required erection rate. The increase of the work to do implies the increase of the required erection rate (given the same time available) as well. The increase of the required erection rate causes an increase of the required workforce for a given productivity of such workforce.

Note that the increase of the required workforce due to an increase of work to do (for a given time available), decreases if the productivity of such workforce increases. This is what we see in the dashed box.

This facts cause other events.

The increased number of required resources causes a flow of incoming resources, which in turn determines an increase of the current or available workforce (closing the gap with the required workforce with balancing loop). The increase of available workforce causes the increase of the current erection rate and in turn, the increase of the work done and a reduction of the work to do as well. In the meantime, the further reduction of the available time pushes the increase of the required workforce but, on the other hand, the decrease of the work to do closes a balancing loop because, as mentioned above, this involves a reduction in the required erection rate. Note that the workforce flow-in increases if the tau-in decreases and the current erection rate increases if the productivity increases.

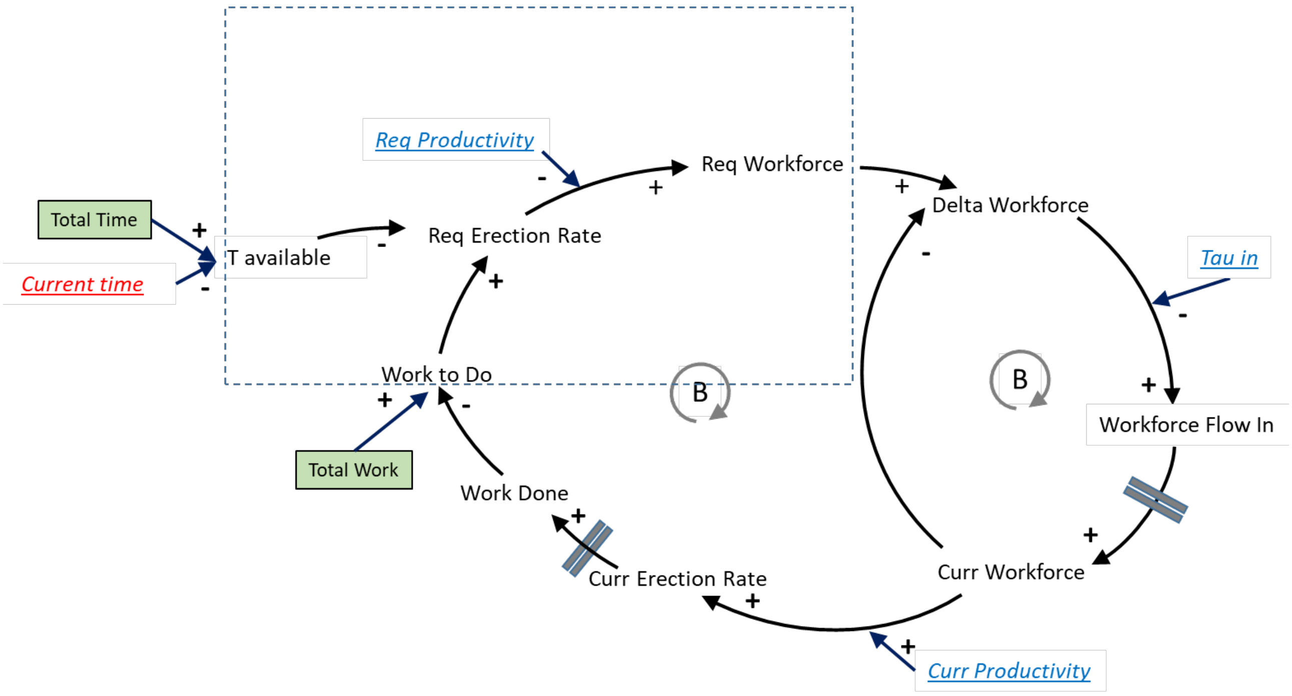

Fig. 5– Causal Loop Diagram of the civil WP during mobilization

The required productivity and the current productivity are supposed equal each other in the following examples. The role of productivity therefore, is to convert the erection rate in a definite level of workforces and vice versa. The level of resources affects the direct cost whereas the low value of tau-in is crucial for the stability at a given total duration T.

In the above CLD we don't see any reinforcing loop. The process is "initiated" by the running current time that reduces the available time. The balancing loops lead the system to steady condition if tau-in is short enough.

However, reinforcing loops may appear if we assume that parameters (tau-in or P) are variables (not shown in the picture).

In fact, it may happen that the current productivity were reduced as the number of resources increased. In this case, two reinforcing loops would be added in the CLD and the system would diverge.

It could happen also that, when the work done is very high (close to the total work to do), then the tau-in becomes longer and longer because it becomes difficult to add new workers for a short period of work. In this case, the import of resources becomes slow. Consequently, the request for resources would grow to catch up until it diverges because the incoming resources are unable to satisfy the request and the available time runs out before the end of the work.

Moreover, in power plants it happens that productivity decreases if the work done increases due to the reduction of available working room for works. This means an additional reinforcing loop too.

2.3.2 – Description of the planned workforce mobilization pattern for constrained structures using CLD

There are processes, such as that one relating to the assembly of piping, which present a very different shape than the civil one. To understand the shape of the resource pattern for piping works, we will start from Figure 6 in which a fluid distribution network (water, steam, air...), typical of many industrial plants, is schematized.

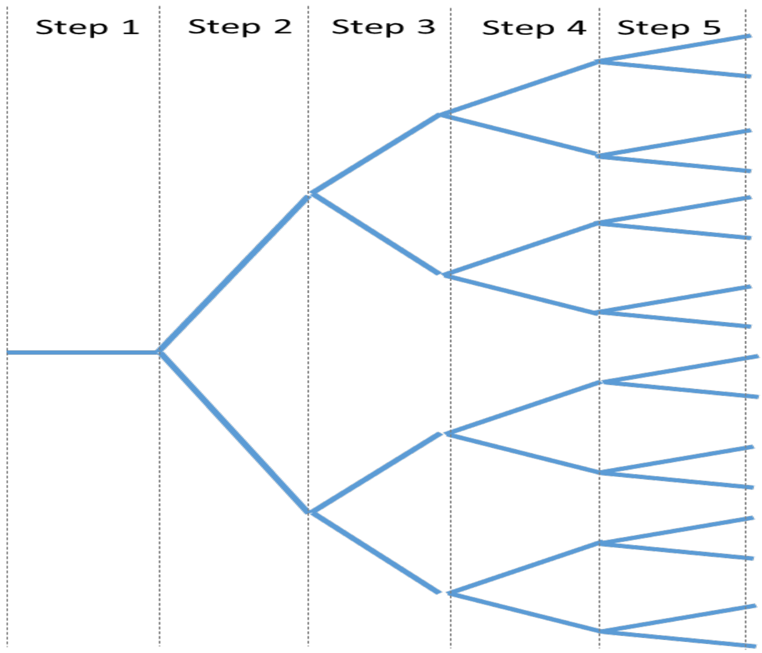

Fig. 6 – Schematic representation of a fluid distribution network

The comparison between piping and civil works patterns shows that, for the assembly of piping, the growth of resources being mobilized in the first two-three months is slower for piping. This can be explained by the fact that, given the same target time T, the resources that can operate in the initial assembly phase of piping are limited as the available work fronts are equally limited. Only after having overcome the initial mobilization phase, as the new available interfaces grow exponentially, it becomes necessary to increase the number of people and parallelize their work in order to respect the given total time.

On the other hand, increasing resources without new work fronts being available, it would only mean reducing productivity.

The increase of resources is therefore concentrated for a limited time in the central phases of assembly. Due to the "slow" start it is necessary to "push" the peak towards values significantly greater than the average value and, consequently, due to the proportionality between the erection rate and W, also the assembly speed reaches a peak equal to 80/35 = 2.28 times the average value with constant productivity. If this initial "bottleneck" effect is neglected in the budgeting phase, delays in implementation will result.

This logic can be represented in the following CLD (Figure 7).

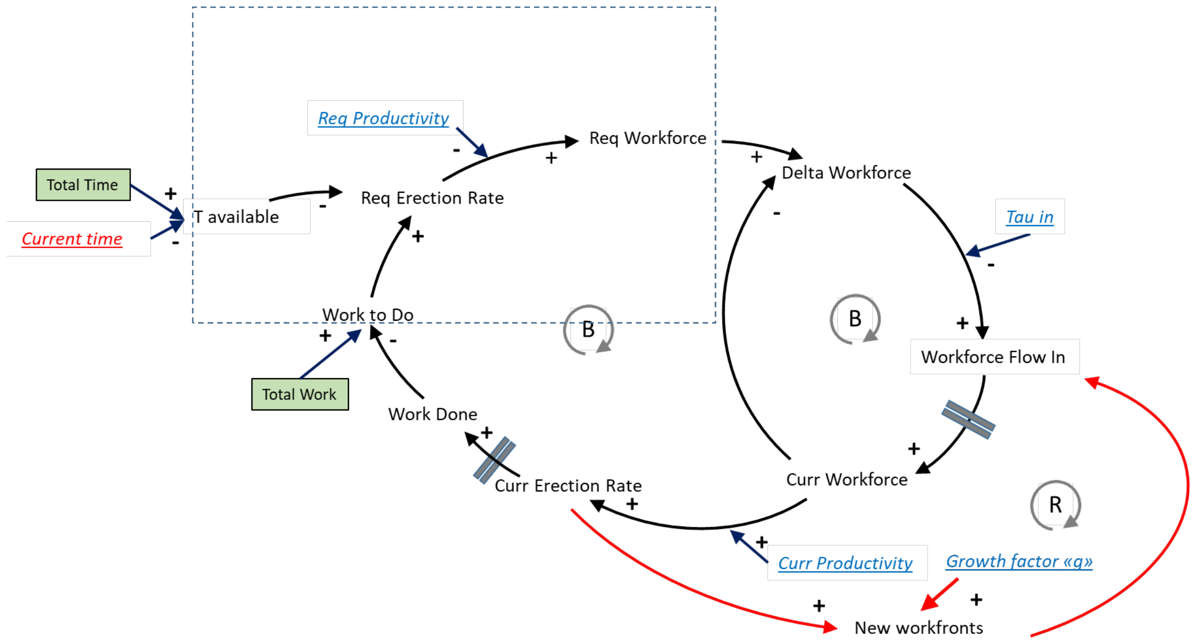

Fig.7– Planned mobilization CLD of piping WP

The CLD of piping erection is the same of civil works one with an additional loop partially represented in red. The additional loop is reinforcing because it allows an increase in the workflow as the current erection rate increases.

Mella and Gazzola (2021) provide an interesting example of reinforcing loop in construction retrieved from the history of Pavia town.

To explain this representation, for this specific case of industrial construction, we can start from the description about how the new work fronts are generated and how this fact allows us to mobilize gradually more and more resources.

This description can be made with reference to the simplified structure of Figure 6 in which the new work fronts grow exponentially in proportion to the items assembled at an intermediate time t. The growth of work fronts (WF) can be described by the following relationship:

$$\text{Delta WF}(t) = k\,(g - 1)\ \text{Delta N}(t)$$

That is, the variation of the WF, i.e. the number of work fronts that are added to the existing ones during the mobilization phase, is proportional (via k) to the growth factor of the structure (g) and to the variation of the items assembled at time t. The “g” factor is characteristic of the structure, in the case of Figure 6, “g” equals 2.

By dividing both terms of the above equation by Delta t, we can say that the increase in working fronts at time t is proportional to the increase in progress at the same time.

This relationship is represented in the CLD by the corresponding red arrow that connects the work done and the new work fronts including the structural growth factor "g".

The following step is to assume that the growth of the work fronts allows the increase in the flow of new resources to be mobilized within the project while substantially maintaining the productivity of the specific processing constant. Therefore, we connect the second part of the red arrow with the flow of resources mobilization.

It should be noted that the WF loop is reinforcing as the greater the assembly speed, the greater the number of new work fronts available and the greater the quantity of resources that can be mobilized and we return to a greater assembly speed.

The above relationship can also be interpreted in another way. In fact, we know that:

$$dN/dt = P*W$$

the assembly speed (dN/Delta t) is equal to the product of the number of resources by their assembly productivity and the growth of the work fronts allows the increase in the flow of new resources, therefore the relationship can also be written:

$$\text{Delta } W(t) / \text{Delta } t = k\ (g-1)\ P\ W(t)$$

Which shows again the exponential trend of resources over time and explains the reason why peak values equal to almost 3 times the average value. When resources reach very high values, the curve reaches a steady value. A very high value for resources in the planning phase does not necessarily mean that it can actually be achieved. This is for various reasons: the peak is too high, there is no availability of short-term manpower or we are close to the demobilization phase, etc.

2.3.3 – The Workforce mobilization for “linear” structures

Let us consider the particular case of a constrained structure in which the growth coefficient of the structure is g = 1.

In this particular case, the workflow term of incoming resources equals zero and therefore the resources can only be constant with a flat pattern. Consequently, the progress of the work grows in a constant linear way. This situation actually occurs for the assembly of those structures, called "linear", in which there is just one work front available at time and therefore there is no possibility of increasing the resources. In this case, the only chances to speed up the progress can be to increase working time and/or working shifts.

Examples of this type of structure are chimneys made of staked cylinder or in-line pipelines (oil pipelines, gas pipelines, etc.) always with side-by-side trunks.

In the reference plant, the steam generator is a case of linear structure. This component was assembled with a "linear" sequence of rectangular duct segments inside which the heat exchange elements called "harps" are also inserted in linear sequence.

Consequently, the ex-post pattern of assembly resources for structural works (Figure 2) approximates the rectangle quite well, having a constant resource portion of its pattern that is rather prolonged over time.

2.3.4 – Description of the planned workforce pattern for demobilization using CLD

The portion of resource patterns during demobilization i.e. the phase of reduction of resources to zero and the simultaneous completion of the work to be done, shows a typical decreasing asymptotic exponential shape. Consequently, we assume to model the demobilization like an exponential function with a time constant tau-out regardless of whether it is a structure without constraints (civil type) or with constraints (piping type).

Based on this hypothesis, it is possible to calculate the amount of work that an initial set of resources W, working with productivity P, is capable of carry on. This amount of work is proportional to the amount of resources present at the moment when the demobilization begins times their productivity P and times the tau-out.

Therefore, during the mobilization phase, it is possible to associate each value of W with the corresponding value of work feasible in demobilization. When this value, added to the work performed in the mobilization phase, is equal to the total work, then it can be considered that the "tipping point" (i.e. the point of greatest presence of resources) has been reached and the system "switches" from the phase of mobilization to that of demobilization (Figure 8).

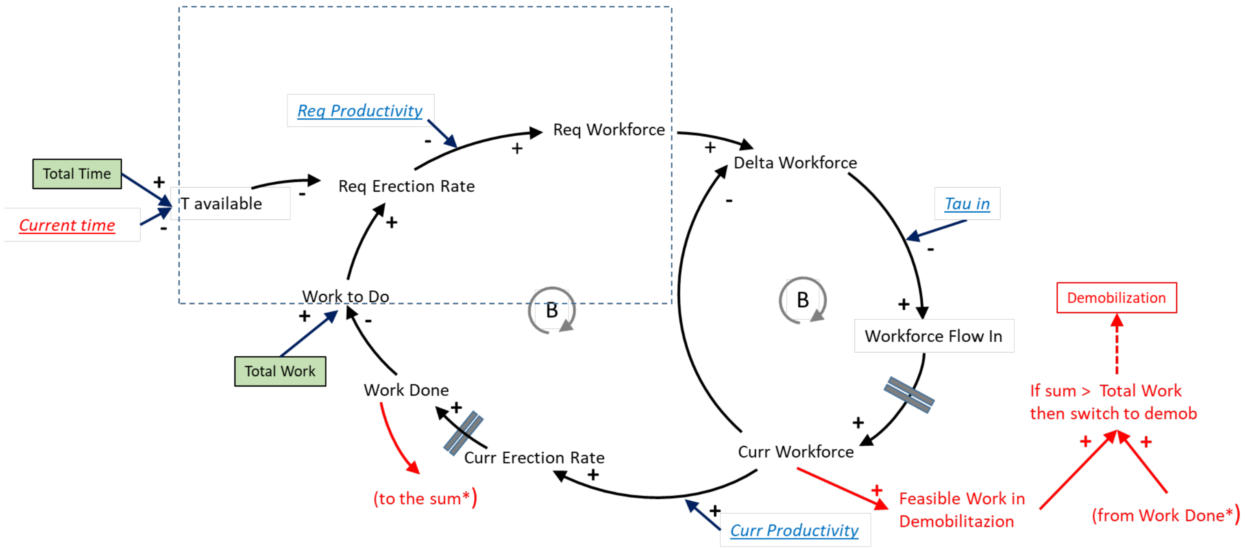

Fig. 8 – Not constrained Mobilization CLD (left) and switch to Demobilization (right)

The figure includes the mobilization CLD of the civil WP (the same applies to the other WPs), and shows that as the current workforce grows, the work that can be done by the latter during the demobilization phase increases. The value of the work feasible during the demobilization phase can be added to the work done at the same time in order to evaluate whether the sum of the two terms has reached the N_T value. If this happens, it means that the "tipping point" has been reached and the demobilization phase begins. The flow of incoming resources stops and the flow of outgoing resources begins. The decreasing resources continue to increase asymptotically the work done until reaching the value of N_T.

3 – Model setup and Findings

3.1 – *Description of the S&F model of the Work Package*

The above study developed by the CLDs about system dynamics provided the necessary theoretical background to explain the logic behind the construction workforce pattern. However, it was just a qualitative analysis whereas we need quantitative results that the Project Manager can use for controlling the project performances. Such further step can be done by using the S&F methodology.

3.2 – Comparison of Workforce planned pattern – Data vs S&F model

With the S&F methodology, a three-level or Stocks (Figure 9) module can represent each WP of our project.

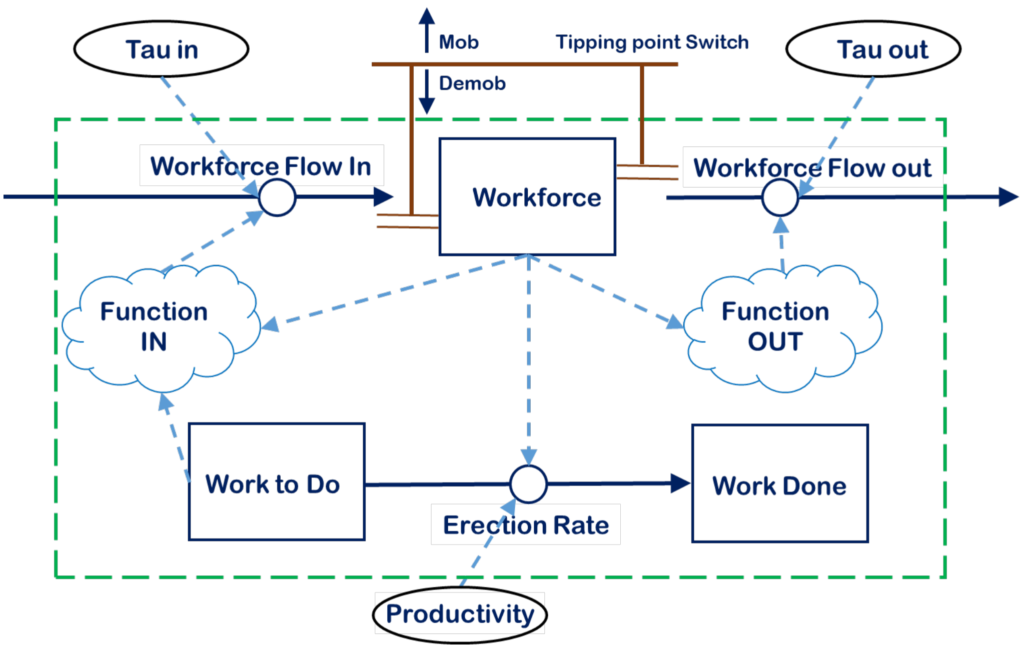

Fig. 9 – The three levels S&F model of a WP – Planned Mobilization and Demobilization

One level represents the Stock of resources available at the construction site on a certain moment, which is determined by the Flow of resources entering during the mobilization phase or leaving during the demobilization one, each of them with the relevant time constant. Two other levels represent respectively the Stock of items to be assembled (Work to Do) and that one of assembled items (Work Done). The Flow of material being assembled, i.e. the assembly speed, equals the assembly workforce times their productivity.

In the following figures, we compare the site data with the pattern of each WP that has been modeled for the planned condition.

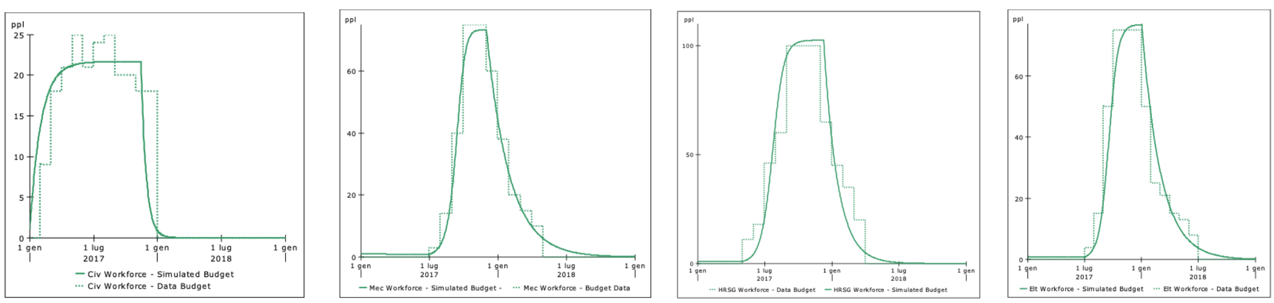

Fig. 10 – Planned workforce of all 4 WPs: Data (dashed) vs model (continue)

Figure 10 shows a very good agreement between the data of the reference project with the output by the model in the planned condition. Obviously, this cannot be considered as a validation of the model but rather as a "calibration" on the reference case. However, the very good agreement between data and curves in the planning phase is a supporting evidence for the validity of the S&F model that was chosen. We will see in the next section, that the agreement between data and model persists even outside the point of "calibration", and in particular, the model fits with the actual patterns too.

The following Table 2 shows the comparison between data and model results for the planned resource patterns. As can be seen from the table, the efforts detected and calculated are very similar each other and this circumstance occurs for the different structural types.

Table 2 – Planned Data vs Model for all the 4 WPs of the reference plant

WP	Structure Type	Effort - Data (man months)	Effort - Model (man months)
Civil	Not Constrained	220	215
Structural	Linear	600	600
Piping	Exponential	350	348
Elt I&C	Mixed (Not constrai-ned-exponential)	426	427

3.3 – *Actual pattern analysis*

The planned pattern of each WP will be a reference during the construction but it will have to take into account the impact of the actual conditions that arise during that period.

Typical variations during construction can concern the workforce productivity P, which generally turns out to be lower than the planned one, the tau-in and tau-out time constants, the limitations of the maximum number of resources or even limitations of workforce entering flow. It is also frequent the scope change (i.e. the change of design and quantities to be assembled) but this case is not considered in this article.

Based on the ex-post actual patterns we realize that the four WPs we are analyzing were subject to the following variations (the actual values in red are lower than the planned values):

Table 3 – Planned vs Actual Data for all 4 WPs

	Item	Productivity (item/ppl/m)		Max Workforce (ppl)		Max Flow (ppl/m)	
WP	**(units)**	**Planned**	**Actual**	**Planned**	**Actual**	**Planned**	**Actual**
Civil	(m3)	46,2	30,5	22	20	-	-
Structural	(ton)	1,67	1,25	100	150	-	-
Piping	(kg)	860	811	80	42	-	-
Elt I&C	(m)	70,6	91,8	80	50	25	12

To simulate these actual variations with the S&F model, we double the three-level model of each WP introduced in Figure 9 in order to create the master (planned) and slave (actual) versions. Variations (i.e. lower productivity, maximum resources, etc) will affect the slave but the error generated by the comparison with the master planned progress, will correct the actual workforce flow in order to keep the target.

In this way, it is possible to simulate the controlled behavior of the actual version like any typical control set (Figure 11) in which the red and green rectangles represent the model of Figure 9. Such a controlling set includes a controller module with controlling parameters: Proportional, Integral and Derivative (PID).

The right setting of the controller is important since it should be the right compromise between a too slow, therefore inefficient, or too fast, therefore instable, correction.

A benefit of the model is the possibility of optimizing the controlling parameters. The use of adaptive regulation is currently being studied.

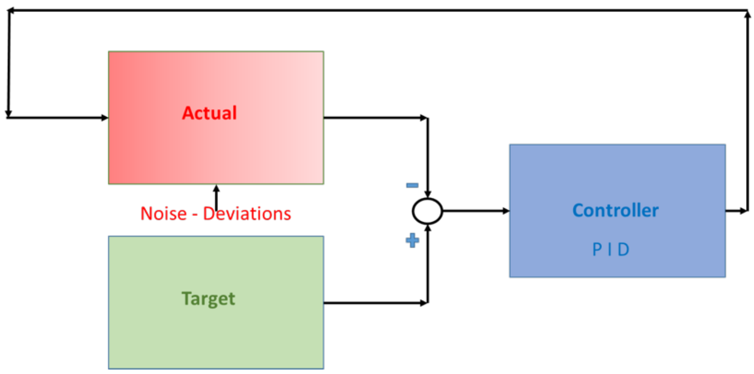

Fig. 11 – Project simulation module master-slave including the Controlling set

To understand the behavior of the controlling system, we can consider the WP of piping assembly (Figure 12).

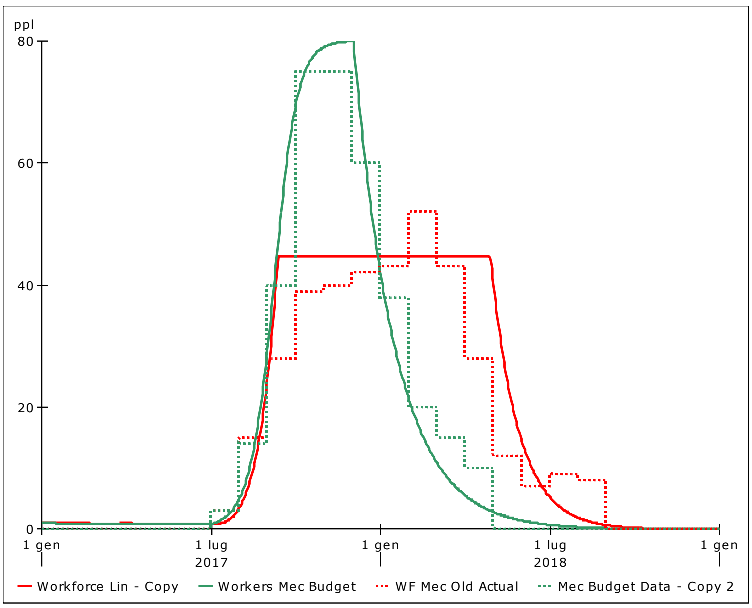

Fig. 12 – Workforce Patterns of the piping WP: target (green) and actual (red), Data (dashed) vs. model (continue)

In Figure 12, we see that the planning (green lines) would have required a peak of 80 workers and, after a couple of months, the demobilization phase should have begun. In reality, it happened that the actual productivity was by 6% lower than planned and the maximum number of resources did not exceed 42 units (see Table 3).

The combination of these two factors i.e. lower productivity and lower workforce peak, plus the controlling action, generated the actual curve represented in red. The actual effort (man months) has increased due to the reduced productivity and the duration has lengthened due to the actual limit for the maximum resources that causes also the maximum assembly speed.

Figure 13 shows the planned and actual trends for all four WPs analyzed.

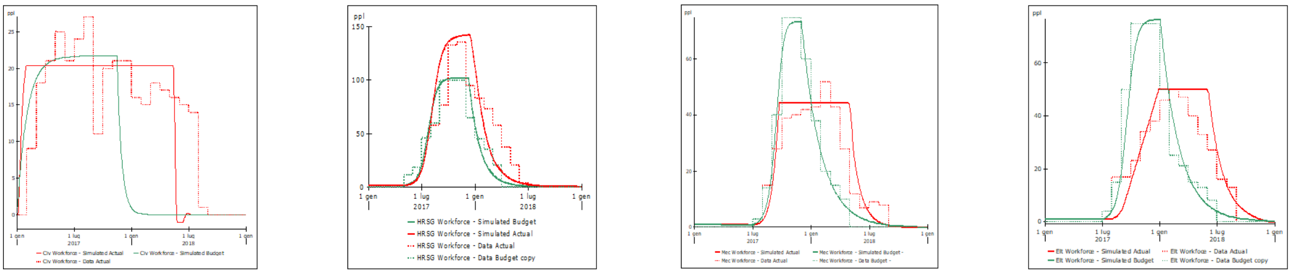

Fig. 13 – Workforce patterns of all 4 WPs: target (green) and actual (red), Data (dashed) vs. model (continue)

3.4 – Overall model result of all WP

In Figure 14 we see the overall combined effect of the four tasks of the reference project that were previously analyzed one by one independently each other. Therefore, we can finally compare the model output with the original data showed in Figure 1. The shape of the target and actual patterns show that the model reflects the "physics" of the dynamic reality.

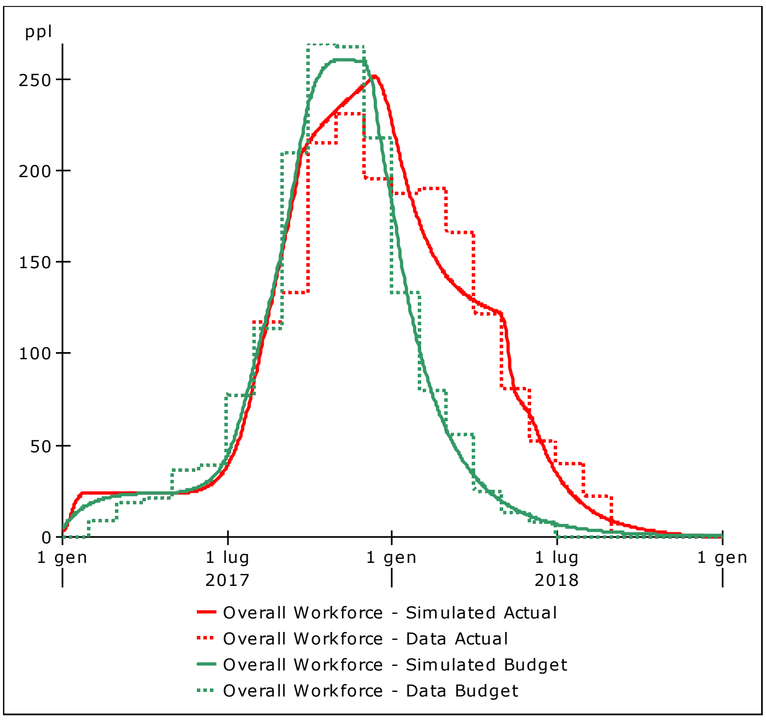

Fig. 14 – Overall pattern of all 4 WPs: target (green) and actual (red), data (dashed) vs model (continue) - Data derives from Fig. 1

To reproduce the logic of links between the different WPs in the model, i.e. the "finish-start" sequence, the relevant input is provided in a specific table as it happens in a typical Gantt schedule. In the resulting overall model, it can also be imposed that the start of a new activity has an impact on the productivity of other activities with which it "interferes", as it happens in reality.

The overall plant work simulation system is therefore made up of four "subsystems", each of them is subject to a feedback between target and actual, each of them with its own dynamics deriving from its own productivity parameters, tau-in, tau-out and structural growth factor "g" to which the dynamics of the PID type control is added. The four subsystems are interconnected each other according to a logical sequence and can influence each other, giving rise to a sort of "dynamic" Gantt whose critical paths and resource patterns can vary depending on disturbances, mutual influences and control dynamics like in reality. A simple schematic representation of the "dynamic" Gantt model is shown in Figure 15.

In the following chapter, we will see some possible applications of the model.

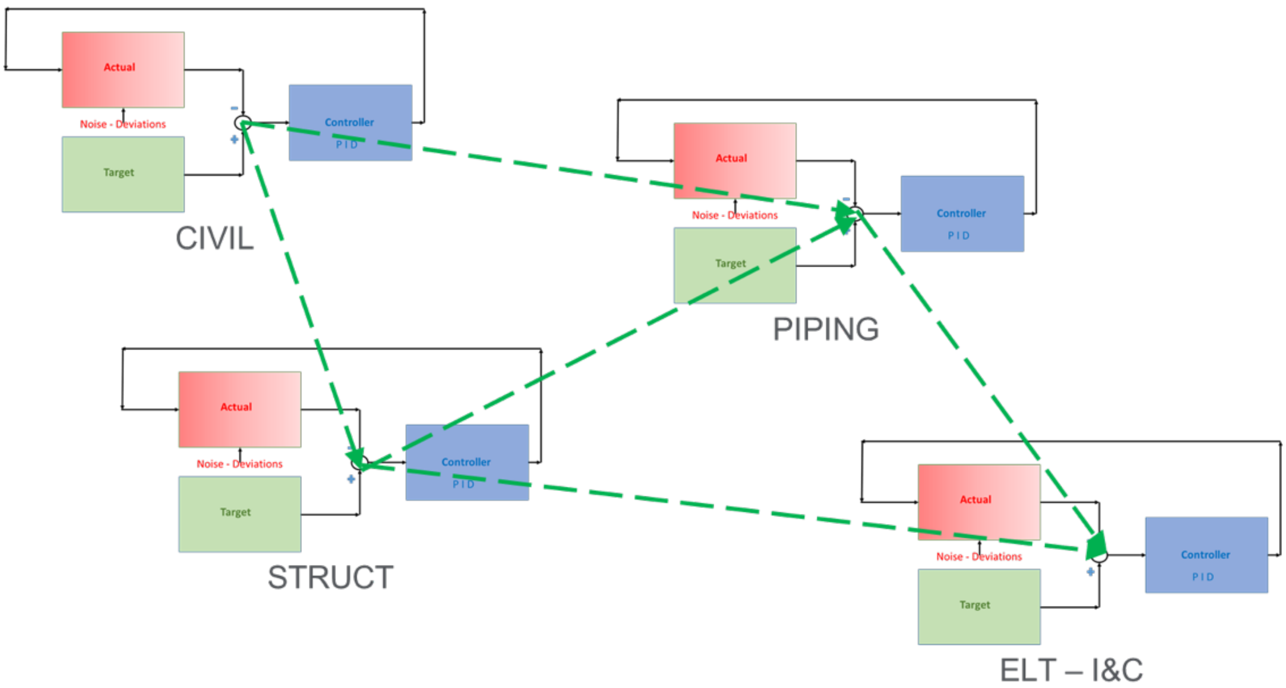

Fig. 15 – Model Network of 4 controlled WPs connected each other in a typical Gantt sequence

4 – Discussion and Examples

Although in Table 2 and Figure 10 we have seen a significant similarity between data (i.e. the workforce pattern of all WPs in planned condition) versus the model output, we do not think it is enough to proof its general validity. In fact, one can argue that such a similarity derives from the fact that the model was "calibrated" with the data.

Such an argument is true, nevertheless there are some qualifying aspects of the model that worth to be mentioned below, and in particular:

1 – the calibration of the model was done after having analyzed the construction planning process with the relevant CLD based on *physical* parameters such as N, W, P, tau-in, tau-out, g;

2 – the analysis of the planning patterns made it possible to "emerge", among other things, the role of the topology of the structure being assembled and in particular the role of the speed with which the new work fronts appear which allows the incoming workforce flow to grow.

3 – the analysis of the construction process clarified the demobilization phase and highlighted, on a physical basis, the moment of transition from the resource mobilization phase to the demobilization one (“tipping point”).

4 – the concept of project control based on feedback that acts on the actual progress starting from the error with the target, reflects exactly what is attempted to be done during construction. This allows a qualitative improvement compared to what is currently done that is only a monitoring of the situation on the field and a final forecast at constant productivity (see "case 2" below);

5 – the fact that the calculated *actual* (not only planned) trend agrees very well with the actual data (obviously after introducing the actual constraints) without further ad hoc adaptations of the model can be considered further evidence of its validity;

The model allows the Project Manager to have real-time forecasted resource pattern with the related peak factors that need to be leveled if necessary, and to display the progress curves in real time. Even if any further tests of the model on other real cases would be useful, it is considered important to underline that, beyond the tests of validity of the model, the method with which it was created makes sense.

Below we see some examples of how to use the model.

Case 1 – “What if analysis” method for optimizing the planning pattern and calculating risk

By using the model from the beginning of any project, it is possible to analyze different scenarios with the aim to minimize costs and risks. In the example in Figure 16 and Table 4, we can compare two hypothesis:

A) the four WPs have the same overlap and *planned* productivity as of the reference project. In the “what if” analysis, the actual productivity and constraints indicated in the previous Table 3 are assumed, which are those of the reference project;

B) the four WPs have the same *planned* productivity as the reference project but the four WPs are lagged each other to get a lower overlap than the reference project. In the “what if” analysis, a higher productivity than the reference project and fewer constraints on maximum resources are assumed during *actual* conditions.

Using the model, it was estimated that, by reducing the overlap of the WPs like in B, there would be an increase in the overall time (in the specific case the overall duration would go from 18 to 19 months), therefore there would be a greater indirect costs. However, the advantage of improved productivities in the new actual conditions would lead to a saving of 365 man months (i.e. -18% than actual in case A). With lagged activities, there would also be other advantages such as the decrease of the workforce peak from almost 300 units down to about 200 units. Improved staff safety and rational management of the construction site can be also achieved.

The purpose of this analysis is precisely to evaluate different scenarios during the start-up phase of the project. It should be noted that, since the system is composed of subsystems, such as the individual WPs, and each of them is "controlled" with feedback, the overall system is very stable.

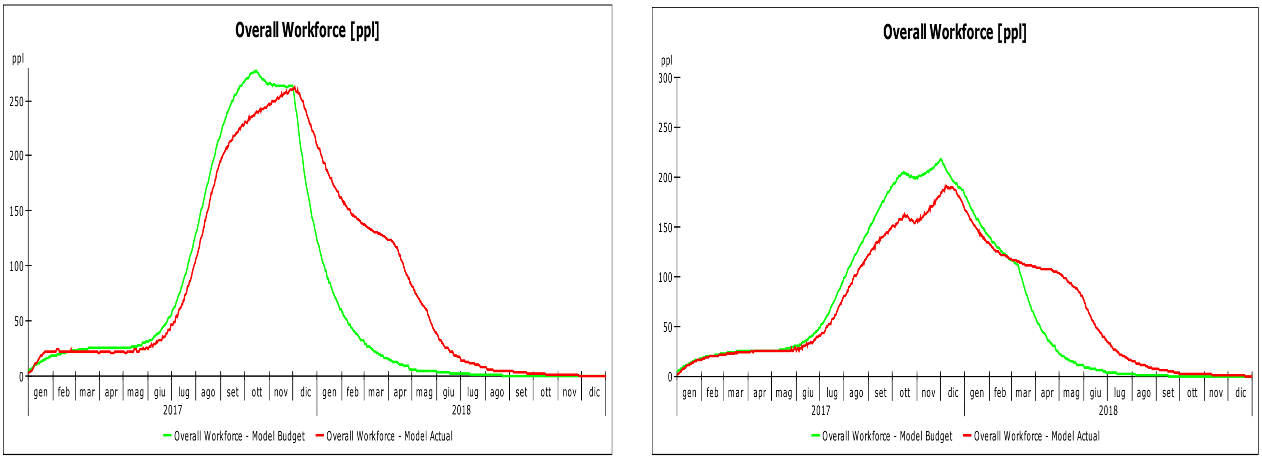

Fig.16 – "What if analysis": high overlap with 300 workers peak (left) vs low overlap with 200 workers peak (right) – planned (green) vs. Actual (red)

Table 4 – Model Output for two overlap scenarios - planned vs Actual

	Planned		Actual	
Case	**Time (months)**	**Effort (man months)**	**Time (months)**	**Effort (man months)**
A – High Overlap	18	1590	18	2010
B – Low Overlap	19	1590	19	1645

Case 2 – Method of recovering the delay caused by disturbances and deviations during construction

Starting from an intermediate date of the project ("cut off" date), it is possible to estimate the future progress ("total job"). In this case, the analysis starts from the resource data and actual progress at the "cut off" date which often do not coincide with those planned for the same date since, generally, projects are understaffed and in delay. With the proposed model, the control system evaluates the corrective action in terms of additional resources required to achieve the target result based on the actual productivity recorded up to the "cut off" date. This allows the Project Manager to evaluate realistic countermeasures.

Figure 17 shows a simple numerical example about how the model solves the problem using the control system.

Case 3 – Model to be used as training simulator

The proposed model allows the creation of very effective summary "dashboards" that are easy to interpret even for non-experts.

In the example of Figure 18, it is possible to see the Schedule and Cost Index of the Earned Value Method as well as some "sliders" by which it is simple to vary hourly costs, productivity, regulatory earnings, etc. for simulation purposes.

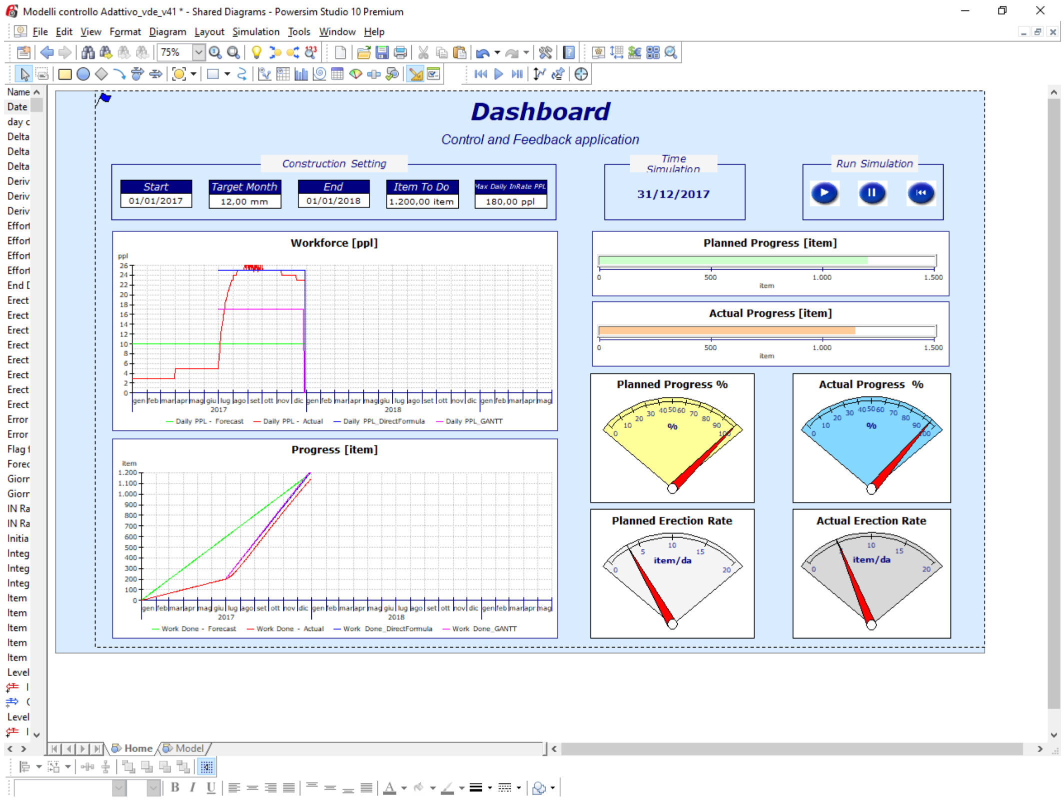

Fig. 17 – Workforce calculation of a single WP understaffed an in delay. The control system assess the correction taking into account the actual productivity

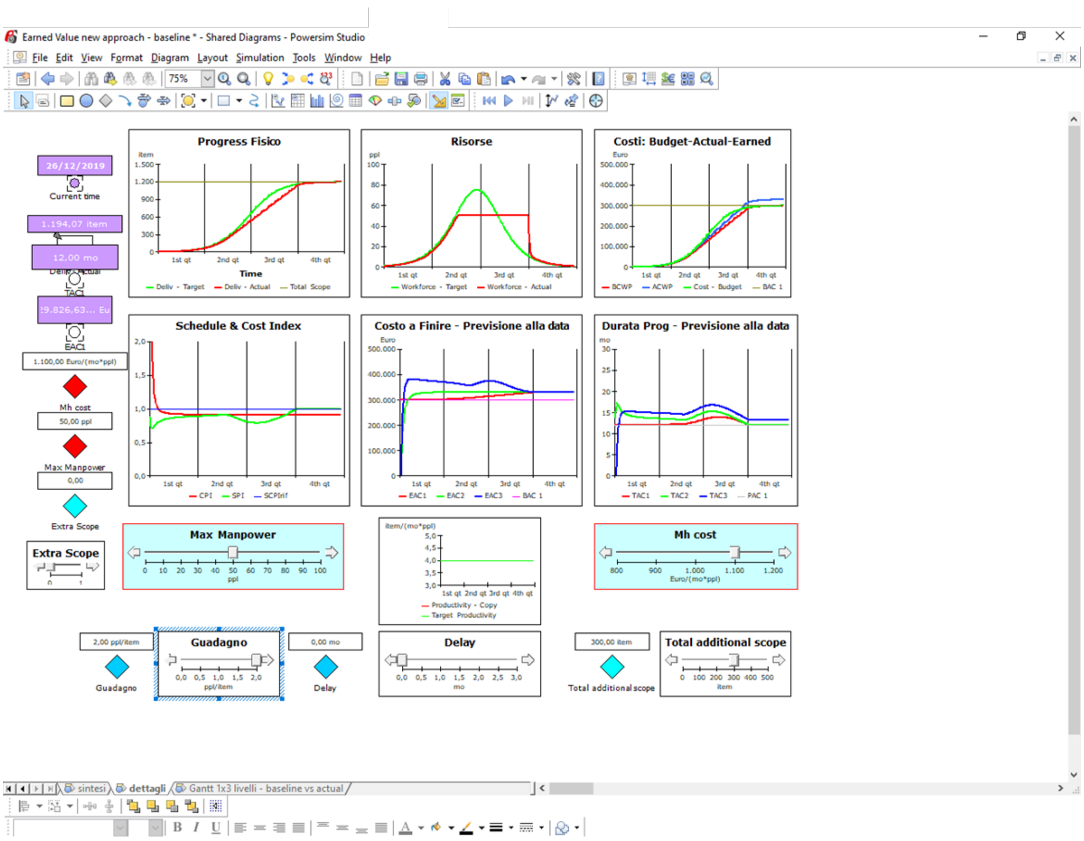

Fig. 18 – Example of Dashboard to simulate the project behavior using the Earned Value Method

5 – Conclusions

This article analyzes the construction process of a generic structure (Work Package) made up of N_T items which is assembled by workforce resources that operate with a standard average physical productivity P (item/ppl/month). The analysis was based on the ex-post patterns of the workforce resources used in a real reference industrial construction (power plant).

The ex-post analysis concerned the four main Work Packages of the reference project i.e. civil construction, structural and piping assembly, electrical and I&C cables laydown. For each process, the workforce pattern was analyzed both for the planned version (target pattern) at the beginning of the construction, as well as the actual one as it was recorded at the end of the construction (Figure 13). The analysis showed that each pattern includes two distinct phases of resource flow: the *mobilization phase* and the *demobilization one.* During the first phase, the resources, starting from zero, arrive at a stationary level that ends with the achievement of maximum presence, called *"tipping point".* The mobilized workforce will assembly items with a given productivity P. After the "tipping point" there is a discontinuity of the workforce flow and the *demobilization phase* starts, it means that resources return to zero and the work is asymptotically completed.

The shape over time of each target mobilization pattern was analyzed qualitatively in terms of Causal Loop Diagrams (CLD), highlighting the role of the main parameters that influence the trend and in particular: scope, workforce, total time, productivity, delay time and the topology of the structure being assembled. In particular, we saw the important role of the limited available time for construction as well as the role of new work fronts available (if any). The limited available time, which is continually decreasing during the construction, has a forcing effect in adding new resources during the mobilization phase. On the contrary, the generation of new work fronts can limit such workforce increase if the structure topology does not allow it. The above analysis included also the dynamic trend of the demobilization patterns, which was similar for all WPs. It was modeled like an exponential outflow of resources as clearly highlighted by the data. This assumption made it possible to calculate the moment of the "tipping point", i.e. the moment in which the transition from the mobilization phase to the demobilization phase occurs.

The *qualitative* analysis based on CLDs was the input for a further quantitative analysis using the Stock and Flow (S&F) simulation method whose output was compared with the available data. In particular, each WP was modeled with a three-level S&F model (Figure 9).

The three-level structure of each WP is duplicated to take into account both the target situation, which acts as master, and the actual situation which acts as slave according to a typical control scheme. Further development of the model is underway to study the optimization of regulation according to adaptive criteria. The concept of structural growth factor has been generalized and has been characterized not only for "exponential" tree structures, but also for "linear" structures. The structural growth factor is crucial due to its effect on the possibility to run parallel work and the consequent workforce peak factors that are generated during the construction. The three-level structure of each WP (master + slave + controller) is connected to that one of the remaining WPs as in a classic Gantt but with the further possibility of taking into account the workforce flow delays and the mutual influences of the different processes. It means to take into account how a single process could influence the productivity of the other processes that take place simultaneously with it (Figure 15). In this way it was possible to compare the final overall pattern (target and actual) of the model with the data collected on the field (Figure 14).

The *quantitative* model that was built to simulate the reference project, allows the Project Manager to be supported by the automatic control against the external noise and workers underperformances. It means the model can calculate the corrective actions necessary to recover from delays and complete the project within the target time. It should be underlined the fact that the model allows the final corrective actions to be calculated taking into account the actual productivity measured up to the cut-off date, i.e. up to the moment in which the progress check is carried out.

It is therefore possible to carry out the "what if" analyzes to quantify the construction cost and risk and generate the progress curves of each WP in real time. The model allows the Project Manager to visualize the progress of the project in a very effective way through synoptic tables easily understandable even by non-experts (Figures 17 and 18). The graphs shown in this article are the output of prototypes of the model. Works to build up a demo of the model are currently in progress at https://powersim.com/case-models.

In *conclusion*, we believe this study provides a contribution to a better forecast estimate of times and costs of construction as well as the scope of achieving the project control during the construction. Therefore, ultimately, we believe the proposed model can contribute to increasing the possibility of success of the projects.

6 – References

Chuen-Tao, L. Y., (1977). *Applicazioni pratiche del Pert e del CPM* – Franco Angeli Editore, Milano Italy

Eden, C., Williams, T., Ackermann F., & Howick, S. (2000). The role of feedback dynamics in disruption and delay on the nature of disruption and delay (D&D) in major projects - *Journal of the Operational Research Society, 51, 291-300, 0160-5682/00*

Flyvbjerg, B. (2011). Over Budget, Over Time, Over and Over Again – Managing Major Projects. Retrived from: https://www.researchgate.net/publication/235953357_Over_Budget_Over_Time_Over_and_Over_Again_Managing_Major_Projects

Flyvbjerg, B. (2014). What You Should Know about Megaproject, and Why: An Overview. *Project Management Journal, vol 45, n.2* Retrived from: https://www.researchgate.net/publication/261411676_What_You_Should_Know_About_Megaprojects_and_Why_An_Overviewfrom DOI:10.1002/pmj.21409

Girmsheid, G., & Brokmann C. (2007). The Inherent Complexity of Large Scale Engineering Project. Research collection.ethz.ch ETH Zurich ETH Library *Originally published in Project Perspective* 29 https://doi.org/10.3929/ethz-a-005994701

Howick, S., Ackermann F., Eden, C., & Williams, T. (2017) – Delays and Disruption in Complex Projects retrived from https://www.researchgate.net/publication/318260077 DOI: 10.1007/978-3-642-27737-5_118-4

Howick, S., & Eden, C. (2001). The impact of disruption and delay when compressing large projects: going for incentives? – *Journal of the Operational Research Society, 52, 26-34, 0160-5682/01*

Iovino, G. (2022). L'Analisi Dinamica applicata al Project Management - *Rivista dell'Ordine degli Ingegneri della Provincia di Roma IO-roma – anno IX N° 1/2022.* Retrived from: https://www.ganttnavigator.com/lanalisi-dinamica-applicata-al-project-management/

Lyneis, J.M., & Ford, D.N. (2007). System Dynamics applied to Project Management: a survey, assessment, and directions for future research. *System Dynamic Review Vol 23, No 2/3 John Wiley&Sons, Ltd.* Retrived on line in Wiley Interscience 157-185 (www.interscience.wiley.com). DOI:10.1002/srd.377

McKinsey & Company (2020). *The next normal in construction – How disruption is reshaping the world's largest ecosystem.* Retrived from mckinsey.com

Meadows, D.H. (2008). *Thinking in Systems – A Primer* – White River Juction (Vermont- USA). Diana Wright, Sustainability Institute – Chelsea Green Publishing

Mella, P., & Gazzola, P. (2021). An historical instance of urban unsustainability that astounds to this day. Systems Research and Behavioral Science, 38(3), 355-367.

PMI's Pulse of Profession (2017). *Success Rates Rise – transforming the high cost of low performance.* 9th Global Project Management Survey

PMI's Global Standard (2018) *Navigating Complexity: a practice guide* Project Management Institute, Inc. ISBN 978-1-62825-036-7.

PricewaterhouseCoopers LLP (2013). *Correcting the course of capital projects - Plan ahead to avoid time and cost overruns down the road.* Retrived from www.pwc.com

Proceedings of the Conference, (2018). *Project management – Driving Complexity PMI Italian Academic Workshop.* University Press – Sapienza Università Editrice. ISBN 978-88-9377-086-6

Senge P. M., (2006). *The fifth Discipline. The Art and Practice of The Learning Organization*. Random House Business Books, London. ISBN 978-88-9391-682-0

Sterman, J.D. (2000). *Business Dynamics – System Thinking and modeling for a Complex World.* Irwin McGraw-Hill

White, J. C., & Sholtes, R. M., (2016). *The Dynamic Progress Method – Using Advanced Simulation to Improve Project Planning and Management*. CRC Press Taylor and Francis Group. ISBN 13: 978-1-4665-0437-0.

APPENDIX

Parameter estimation

The assembly work is usually evaluated in man-hours (or man-months) which represents the estimated amount of hours (or months) of work that the resources will spend to carry out the assembly work.

In the article the assembly work is called **Effort** and is measured in man-months. In particular, the overall effort of the four WPs examined in this article is 1596 man-months.

Starting from the definition of effort, then we can define the "**Specific Effort**" (man-hours/item) being the value of assembly man-hours per single element (item) to be assembled.

The specific effort is a parameter known to practitioners with the term of "**standard hours**", i.e. the man-hours statistically necessary to carry out a specific process like piping welding, cable commissioning, cable laying, etc. Such a values are available in the technical literature.

The reciprocal value of the specific effort is the **Physical Productivity** (item/man-month) or the quantity of items that can be assembled per man-month of work.

Starting from the definition of productivity, we can define the concept of **Work Package** (**WP**). In the article, the term WP is used to indicate a subset of the works that are part of the total construction, characterized by a typical, homogeneous average productivity of the resources characteristic of that specific works.

The structure to be assembled within a WP is schematized as the set of a rather large number of relatively small elements, similar each other, that we call **granular hypothesis**.

We indicate by $\mathbf{N_T}$ the total number of elements that we need to be assembled for a generic WP, also called "**Scope**".

We therefore have the following variables:

N(t) is the work performed at time t (also called **Progress** or **Work Done** at time t)

$\mathbf{N_T - N(t)}$ is the work remaining to be performed (also called **Work to Do**) at time t

T is the target duration of the job

$\mathbf{N_T/T}$ is the average target mounting speed or initial **Erection Rate** (assembly speed)

W(t) are the resources available at site on time t

$\mathbf{N_T/P}$ are the total man months to assembly the WP that we called **Effort**

dN/dt = W(t)*P is the instantaneous Erection Rate

tau-in and **tau-out** are delays respectively relating to the flow of resources entering and leaving the project.